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THE INFLUENCE OF THE EARTH'S ROTATION UPON THE LATERAL EROSION OF STREAMS[1]

HENRY M. EAKIN

INTRODUCTION

It is a well-known fact that rotation of the earth upon its axis sets up a tendency in bodies in motion upon its surface to deviate from a straight course, in the northern hemisphere to the right, and in the southern, to the left. Different writers[2] have considered the possible results of this tendency in modifying stream erosion, but in general little importance has been attached to it, striking results of its operation not being commonly observed.

The most satisfactory analysis of the problem is Gilbert's, in which he notes certain processes involved in stream erosion not usually considered and endeavors to make a quantitative measurement of the effect of the deflective force acting relative to them. He points out that centrifugal force is developed on the curves of meandering streams. Velocity being a factor of this force, so-called "threads" of higher velocity will tend more strongly toward the outer bank on curves. The rotational deflective force depending also upon velocity will affect the "threads" of higher velocity more strongly. The effect of this stronger tendency of the swifter threads one way or the other he expresses as a "selective influence," whereby they migrate nearer one bank or the other, displacing threads of lower velocity and accelerating lateral erosion. In the northern hemisphere the rotational deflective force acts in conjunction with centrifugal force on right curves, and on left curves in opposition to it. Consequently the locus of maximum velocity would be shifted toward the outer bank more strongly on right curves than on left curves, the cross-section profiles of the stream would be correspondingly modified, and a difference in lateral erosion would ensue. The efficiency of rotation to produce appreciable results is advocated only in "connection with and as an adjunct to lateral wear by means of curvature."

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[1] Published by permission of the Director of the U.S. Geological Survey.

[2] Dunker, *Zeitsch. für die gesammten Naturwissenschaften* (1875), 463; Klockmann, *Jahrb. Preuss. Geol. Landesamt* (1882); Geikie, *Textbook of Geol.*, I, 23; Chamberlin and Salisbury, *Geology*, I, 184; Jefferson, *Bull. Geol. Soc. Am.*, XVII, 333–50; Gilbert, *Am. Jour. Sci.*, 3d ser., XXVII, 427.

In certain Alaska streams the writer has noted a strong predominance of erosion on the right bank, shown by asymmetry in the position of the river with respect to the flood plain, the distribution of bluffs on the right and left limits, and in the distribution of bars and islands relative to cut banks. In the case of the Yukon, in the last 600 miles of its course the flood plain, 20 to 50 miles wide, is almost entirely on the left-hand side. It flows close to the right valley wall almost the entire distance, often with steep, fresh-cut bluffs in bed-rock. The left bank is commonly alluvium, bed-rock being encountered only once in this distance. And in the single instance mentioned, opposite the mouth of the Melozi River, a large delta has been built out by the tributary stream, literally crowding the larger river over to the left valley wall. In this part the Yukon is essentially without meanders, being characterized by long straight reaches and gentle curves.

Also of great significance in the case of the Yukon is the behavior of driftwood and floating débris. Such material is almost entirely absent from the left bank, but is plentiful on the right. And in flood time, when the current is well supplied with such material, its distribution on the stream surface is most striking. It is confined almost entirely to the right half, and often to a much smaller space along the right bank. Eddies along the right limit are often crowded with drift; along the left never, so far as observed. At Nulato, where the river is about a mile wide, the natives get a large supply of wood by catching drift logs, and they seldom have to go more than 300 feet from the right bank to secure them.

The problems presented by these conditions have stimulated study, which has led to an analysis of the processes of river erosion considerably different from that described above. In the following pages, after a simple review of the principles to which the deflective force is due, it is intended to emphasize its greater strength in higher latitudes, to show that its expression in unbalanced lateral erosion is least in streams where meanders are in process of development and greatest in streams with straight courses—that the force is opposed to the development of meanders and in high latitudes may fully account for the conditions described above.

THE DEFLECTING FORCE OF THE EARTH'S ROTATION

For a brief elementary review of the principles which give rise to this deflecting force, we may imagine the earth perfectly smooth and friction eliminated. This force has two modes of origin, one being active when the relative motion is in an east-and-west direction, the other when the relative motion is north and south. In case the relative motion is not in any true direction, both modes are active at once, and the deflecting force has two components arising in different ways, but acting similarly.

To get these components distinctly in mind we may consider them separately. (For convenience the following abbreviations may be used: F_g=force of gravity, F_c=centrifugal force, F_d=deflective force of the earth's rotation.)

COMPONENT OF DEFLECTING FORCE ARISING FROM EAST-AND-WEST RELATIVE MOTION

An object upon the earth's surface and at rest with respect to it has a certain gyratory velocity equal to that of the earth's surface at the same latitude. This gyratory motion gives rise to a centrifugal force, acting in a plane normal to the axis of rotation. Owing to the nature of the ellipticity of the earth, a gradient is furnished at every point whereby a part of the force of gravity is caused to oppose and exactly counterbalance this centrifugal force, and the object would have no tendency to move either toward or away from the equator.

However, if the object had an easterly motion with respect to the earth's surface, it is readily seen that the centrifugal force would be increased and the ellipticity of the earth's surface would no longer be sufficient to cause its counteraction by gravity. The resultant force would furnish a component acting along the earth's surface toward the equator to the right in the northern hemisphere and to the left in the southern. Again, if the object had a westerly motion relative to the earth's surface, the centrifugal force would be decreased and the ellipticity of the earth, being more than a match for it, the object would tend to slide down the gradient toward the poles, to the right in the northern hemisphere, with respect to the direction of its relative motion, and in the southern hemisphere to the left. These principles do not require that the object move directly east or west, but operate so long as there is an easterly or westerly component in its relative motion.

COMPONENT OF F_d ARISING FROM NORTH-AND-SOUTH RELATIVE MOTION

Another component of the deflecting force of the earth's rotation arises when the relative motion is in a northerly or southerly direction. Suppose an object at rest with respect to the earth's surface at a latitude of parallel *A* be acted upon by a force causing it to move to a higher latitude of parallel *B*. At parallel *A* the object had a certain gyratory velocity corresponding with a point in the circle *A*. Being drawn toward the center of gyration in moving to a smaller circle, this gyratory velocity is accelerated according to the law of conservation of angular momentum. And since the gyratory velocity of a point in Circle *B* is less than that of a point in Circle *A*, and the gyratory velocity of the object is greater than that of a point in Circle *A*, the object has come to have a gyratory velocity very different from the earth's surface at the same latitude.

This difference would give the object a relative motion in an easterly direction, to the right in the northern hemisphere and in the southern hemisphere to the left.

If the object were at rest at Circle *B* and were caused to move to Circle *A*, the reverse of the above case would be true. The actual gyratory velocity of the object would be decreased according to the same law, and the earth's surface would have a higher velocity at Circle *A* than at Circle *B*. The object would have gained a negative component of velocity in a westerly direction with respect to the earth's surface, and, as before, the deviation would be to the right in the northern hemisphere and to the left in the southern. In either case should the object have, at the start, a relative motion, the same principles would be effective.

EFFECT OF F_d ON OBJECTS MOVING IN FIXED COURSES

Obviously, if the object were not free to move as these forces would direct it, but were constrained to move in a fixed channel, the deflecting force would cause it to press against the side of the channel. Now, if the channel were along a meridian, only one component of the deflecting force would be active, or, if along a parallel, the other alone. But if the channel were in any other direction, the movement of the object would have both a north-and-south and an east-and-west component of motion, and both components of the deflecting force would operate proportionately to the components of relative motion from which they arise. And since, according to Ferrel,[1] the amount of the deflecting force arising from an east-and-west relative motion is exactly equal to the amount due to a north-and-south relative motion under similar conditions, it follows that at any given latitude for the same rate of relative motion, the deflecting force is constant, regardless of the direction of the relative motion.

MEASUREMENT OF F_d

The amount of this deflecting force varies with the rate of relative motion and the latitude.

Using Ferrel's formula,[2] $\frac{F_d}{g_m}=\frac{2NS \sin L}{9.806}$ (N = gyratory velocity of the earth in terms of the radius; S = rate of relative motion; sin L = sin. of the angle of lat.; g = accelerative force of gravity), and adopting arbitrarily a definite rate of relative motion of 2 meters per second, or 4½ miles per hour, the expression of the deflecting force in terms of the force of gravity for each fifth degree of latitude is given in column 2 of Table I.

Taking the amount of the deflecting force at the fifth degree of latitude as a unit of measurement, the amount active at each fifth degree of latitude is given in round numbers in the third column of Table I.

For comparison with the more familiar effect of F_c as developed on curves, radii of curvature have been computed which would

[1] Ferrel, *Popular Treatise on the Winds*, 42–88.

[2] Ferrel, *loc. cit.*

generate F_c, approximately equivalent in effectiveness to the deflective force operative under the same conditions at each fifth degree of latitude. These figures are given in column 4, Table I. The same velocity is assumed as in the former calculations. (In these computations a symmetrical arrangement of velocities with respect to a central maximum, decreasing directly with the distance from the center to zero at the margins, has been assumed. This introduces an error which gives a greater relative value to F_c and adds to the value of the radii computed. This error varies with the actual arrangement of velocities in the stream, but probably would never amount to more than a small percentage.)

TABLE I

Lat.	$\frac{F_d}{F_g}$	Ratio	R
5	.00000260	1	65.00
10	.00000516	1.9	33.0
15	.00000770	2.9	22.0
20	.00001018	3.9	16.0
25	.00001258	4.8	13.0
30	.00001488	5.7	11.0
35	.00001706	6.5	10.0
40	.00001912	7.3	8.6
45	.00002104	8.0	8.0
50	.00002278	8.7	7.3
55	.00002438	9.3	6.8
60	.00002576	9.9	6.5
65	.00002696	10.3	6.2
70	.00002796	10.7	6.0
75	.00002874	11.0	5.8
80	.00002930	11.2	5.7
85	.00002962	11.3	5.66
90	.00002974	11.4	5.60

RÔLE OF F_d AMONG THE FORCES OF FLOW

In studying the movements of water in a normal river we have to do with three forces that are setting up and directing currents: F_g acting down the general stream gradient, causing the primary current, and F_c and F_d arising from this primary movement and acting always at right angles to the direction of flow, F_c always toward the outer bank on curves and F_d always to the right in the northern hemisphere, to which the study will be confined in the following pages.

Each particle in motion feeling a lateral impulse, whether from F_c or F_d, will tend to move in that direction. For simplicity, we may take the case of a stream acted upon by F_d only. The lateral impulse will be transmitted to the right, so that each particle will feel the combined impulse of all those to the left in strata of equal pressure. The tendency will be for all to move to the right until a lateral gradient is established that will furnish at each point an equal impulse in the opposite direction. In a stream with velocities in each stratum of equal pressure arranged symmetrically with respect to the center, this gradient would be a compound curve with a general inclination to the left (see *aa*, Fig. 1).

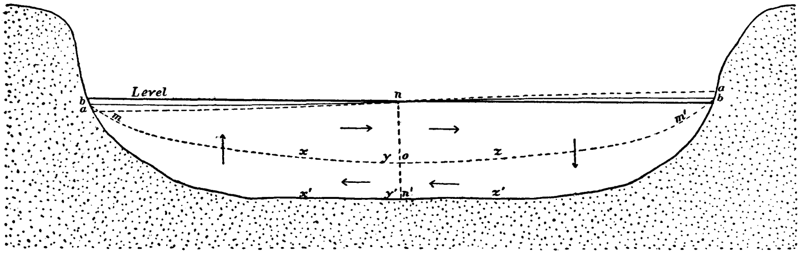

Fig. 1

But this potential gradient is never established. The velocities of the particles at x', y', z' (Fig. 1), being less than those at x, y, z, are unable to support the same lateral gradient, so that, before the potential lateral gradient for x, y, z, is established, some lesser gradient will cause a movement of x', y', z' to the left. This actual gradient would be constant for any set of conditions and would also be a compound curve (see *bb*, Fig. 1).

At some point between x and x', the force of F_d will just equal the opposing impulse from the actual lateral gradient. At this point no lateral movement will take place. Above it movement to the right will occur, below it, movement to the left. Between other points similarly related, like conditions will hold, giving a zone in which lateral movement is absent (*mm'*, Fig. 1).

Since the curve representing the potential gradient is stronger than that of the actual and the area of the cross-section of the stream is practically constant, at some point the two must coincide, and no vertical movement will occur. And so, for each stratum of equal pressure we will have a zone (*nn′*, Fig. 1) without vertical movement. To the right all particles will have a downward component of motion, to the left, an upward component. At the point of intersection of *mm′* and *nn′* all impulses are balanced save F_g acting down the stream gradient.

The stream has, then, a central axis about which a sort of revolution takes place. Under the influence of either F_c or F_d or of both, the stream progresses with a boring movement.

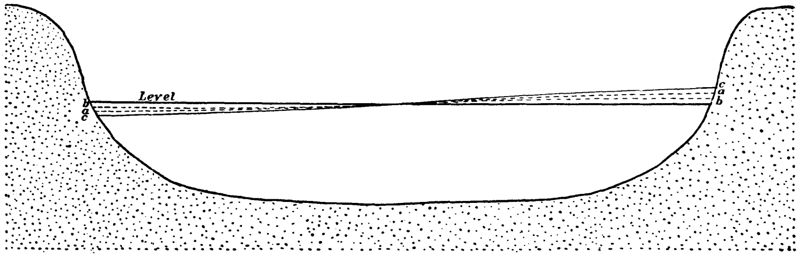

FIG. 2

Being the last factor that can be closely approximated, we may take the potential lateral gradient of the stratum of maximum velocities on the right and left curves of a meandering stream as a measure of the relative tendency of lateral erosion.

On the right curves F_c and F_d will combine. This condition is expressed graphically in Fig. 2, in which *aa′* represents the gradient arising from F_c, *bb′*, that from F_d, and *cc′*, the resultant.

The condition of left curves is illustrated in Fig. 3, *aa′* representing the potential gradient due to F_c, *bb′*, the potential gradient due to F_d with the inclination to the right, and *cc′*, the resultant potential gradient, being the mean.

Mathematically the potential lateral gradients on right and left curves may be computed and compared.

Using Ferrel's formulae for F_c and F_d and the data of Humphreys and Abbot on the Mississippi at Columbus, Ky., the potential lateral gradient would be 18 per cent stronger on the right curves. In this case, however, the velocity data are taken from measurements on a straight reach of the river having a very symmetrical profile. The distribution of velocities being very different on curves, different relations would probably hold between the mean velocity and mean squared velocity, and the above ratio would be changed. The computation, the result of which is given above, involves less assumption than any other method of attacking the problem discovered and the figure, 18 per cent, may be safely considered of the same order of magnitude as that expressing the actual difference of potential lateral gradients on right-and-left curves in this case. The relation between potential lateral gradient and consequent lateral erosion varies with other factors so that an attempt to compare the actual erosion on right-and-left curves would be idle. It is readily seen that, as the radius of curvature increases, the relative value of F_c decreases, until on straight reaches it becomes zero. On straight reaches, then, F_d is acting alone, and the tendency is 100 per cent to the right, its strength depending on the velocity of the stream and the latitude.

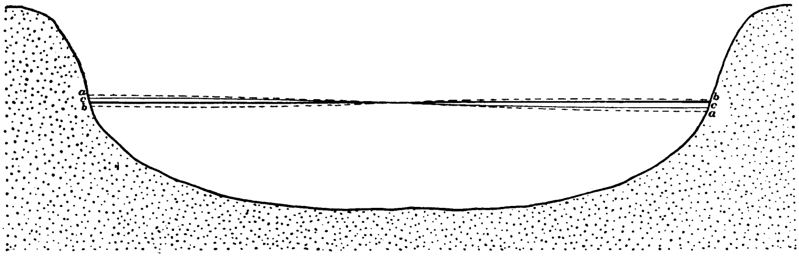

FIG. 3

BORING CURRENTS IN A MEANDERING STREAM

In a meandering stream the potential lateral gradient is reversed on each successive bend. The tendency is for all particles in motion to move toward the outer bank, establishing an actual lateral gradient corresponding to the potential. For a period, friction being low, the actual gradient will be high, since the momentum of the boring currents developed on the preceding curve must be checked and lateral inertia overcome before the boring currents normal to the reversed gradient gain headway. But as such lateral currents are accelerated, friction increases. Friction in that part of the current moving in a positive direction or with the lateral force consumes part of the energy of the lateral impulse so that the actual gradient is lowered. Friction in the part of the current moving in the negative direction consumes part of the accelerative force of the actual gradient.

A condition of equilibrium is reached when the actual gradient becomes such that it is just maintained by the excess of lateral impulse over friction in the positive part of the current and whose accelerative force is balanced by friction in the negative part of the current. This adjustment is made by the shifting of the stratum of non-lateral movement which alters the relative proportions of the positive and negative parts of the current. The higher the actual gradient the larger will be the negative part of the current. As acceleration goes on and the actual gradient becomes less, that part of the current having a negative component of motion becomes more and more closely confined to the bottom of the channel and its efficiency in handling débris correspondingly increased. The condition of equilibrium would represent the maximum of efficiency. That such a condition is not represented in much of the course of a meandering stream is sure. That it is represented in any part is not certain.

BORING CURRENTS IN A STRAIGHT STREAM

On straight reaches no reversal occurs. The condition of equilibrium between lateral forces and friction should be established. Therefore F_d, operating on straight reaches, should be immensely more effective in directing lateral erosion than an equivalent amount of lateral force operating in a meandering stream.

As pointed out by Hagen,[1] Herschel,[2] and others, the power of flowing water to erode its channel depends very largely upon the swirls, eddies, and such inner movements of particles among themselves. Such minor movements might well be called the teeth of the current, it being for the most part their action that wrests material from the bank or the bed of the stream and places it in proper relation to the current to be transported. These minor movements are due to friction between parts of the current, differing in velocity. Their strength and effectiveness depend upon the amount of difference in velocity in a given distance.

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[1] Hagen, *Handbuch der Wasserboukunst*, Part II, Art. 21.

[2] Herschel, *Jour. Franklin Inst.*, 3d ser., LXXV, 401.

The lateral shifting of the locus of maximum velocity and the downward deflection of the stronger upper currents adjacent to the outer bank on curves mark these points as loci of maximum erosion. But equally important in the development of meanders is the deposition of the débris resulting from the cut, normally on the inside of the next curve below the cut, and on the same side. Early in the development of a meander the lateral currents are weak. The débris-laden currents are not shifted far toward the center of the stream before the reversal occurs, their carrying power is changed, and deposition takes place. In more developed meanders the lateral currents being stronger, the loaded parts of the currents are shifted farther and carry their burden a greater distance. In development of meanders, then, the débris is deposited farther and farther from its source, but normally on the same side. When the meanders are strongly enough developed, the load should be shifted entirely across the channel and back again on subsequent curves, and in this may lie an important factor in controlling the width of meander belts.

If, however, in the case of a stream having a straight course, currents are set up by a force other than that due to curvature, the débris will be shifted constantly in the same direction. There will be no deposition below the cut on the same side, and consequently no deflection of the stream. The lateral currents, being constantly in one direction, will mark one side of the stream for dominant cut, and the other for maximum fill.

Whether due to F_c or F_d, the selective cut and fill due to the lateral currents introduce and maintain an asymmetry in the channel profile which, in turn, further modifies the distribution of mass and consequently of velocities in the stream cross-section. The result is to accentuate the selective cut and fill due directly to the lateral currents. The slightly increased depth on the side of the stream toward which the lateral force acts furnishes still another, though probably small, factor in favor of the same selective erosion.

If the foregoing principles are true, we have an adequate explanation of the peculiarities shown by the Yukon and other Alaska streams.

The Tanana River, the largest tributary of the Yukon, in the last 200 miles cuts bed-rock only on the right side and has almost all of its extensive flood plain on the left side. The lower Koyukuk has broad flats to the left and usually rock-cut banks on the right. Spurr notes a similar condition in the Kuskokwim, and Maddren in the Innoko. Though lacking the absolute data on which to base definite measurements of the effect of rotational deflection, the general knowledge of the streams mentioned above seems sufficient to establish the fact of its notable operation in high latitudes. That other causes may produce asymmetrical valleys is not denied. If a larger amount of rock débris is supplied by the tributaries on one side than on the other, the tendency is certainly to crowd the main stream to the opposite valley wall. The thawing of the bank most exposed to the sun would favor greater erosion in that direction. A tilting of the landmass would favor a widening of the meanders on the down-tilted side, but any moderate tilting would have but little direct effect on the lateral erosion of a stream. In affecting the carrying power of the tributaries, however, a notable shifting in the direction of the down-tilting should result.

However, these processes, singly or combined, cannot account for all the peculiarities observed in the Alaska streams and in the lower Yukon, the most striking instance of unbalanced erosion, there is no evidence of their operation at all.

Reasoning that, if such notable difference in lateral erosion should be effected in high latitudes, rivers in lower latitudes should show the result of the same influence to some lesser degree, the Missouri River was chosen for comparison. The Missouri has a well-developed flood plain, meanders broadly, and has been engaged in progressive de-gradation probably since late Pleistocene time. The summary results of all the factors directing its erosion during this period of time should be expressed in the present condition of the river and its valley.

The distribution of the flood plain with respect to the river was measured on the compiled Index Map of the Missouri River Commission, between Sioux City, Ia., and Kansas City, Mo. The results were:

Between the river and the left valley wall, 1,370 sq. miles.
Between the river and right valley wall, 312 sq. miles.

In the upper part of the river, from Fort Benton, Mont., to Sioux City, Ia., we still have what might be termed the first generation of meanders, that is, they are still in a developmental stage and swing first against one valley wall and then the other.

The form of these meanders, of such simple history, is significant. Those to the left of the mean axis of the stream are as a rule sharper than those to the right, the river is in contact with the right valley wall more often than with the left, and those reaches where the river is in contact with the right valley are longer generally than those where the contact is with the left valley wall. This latter characteristic becomes more and more notable down-stream.

In the reach from Fort Benton to Sioux City meanders have been cut off in five cases. Of these, four are on the left side of the stream and one on the right. However, in the case of the individual meander on the right, instead of receding from the loop, as is normal when cut off by differential migration, the river is at present encroaching upon it, making it very probable that the case represents domestic piracy rather than the former process. In each test stronger erosion on the right seems evident.

The influence of the earth's rotation, then, is to unbalance the lateral erosion of streams, in the northern hemisphere directing the stronger erosion on the right bank, and in the southern, on the left. The deflective force is much stronger in the higher latitudes. Its influence is felt by streams both with and without meandering courses and is most effective in streams with straight courses. Examination of streams in both high and mean latitudes reveals conditions of unbalanced lateral erosion that seem best interpreted as the result of rotational deflection.